A Comparison of Natural and Petroleum Resource Development Related Fluxes of Metals, Hydrocarbons and Nitrogen, Phosphorus and Silicon to the Beaufort Sea

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A COMPARISON OF NATURAL AND PETROLEUM RESOURCE DEVELOPMENT RELATED FLUXES OF METALS, HYDROCARBONS AND NITROGEN, PHOSPHORUS AND SILICON TO THE BEAUFORT SEA

by
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Une approche d'équilibre de masse géochimique a été utilisée pour comparer l'écoulement naturel de métaux lourds et d'hydrocarbures du fleuve Mackenzie dans la mer de Beaufort à l'écoulement prévu dû à l'homme de métaux lourds et d'hydrocarbures provenant des activités projetées de production d'hydrocarbures sur la plate-forme de la mer de Beaufort. Des échelles temporelles et géographiques ont été déterminées pour les polluants particuliers à la zone estuarienne du fleuve Mackenzie et de la mer de Beaufort. L'équilibre de masse géochimique est une première étape utile pour évaluer les effets possibles de l'activité industrielle sur la zone côtière; c'est dans le cadre de l'estuaire physico-chimique que les questions de la biodisponibilité, de la bioaccumulation et finalement de l'effet biologique peuvent être abordées.

Les apports naturels dans la mer de Beaufort sont dominés par le fleuve Mackenzie qui déverse chaque année environ 3.7×10^{11} m^3 d'eau et 8.7×10^7 m^3 de macroparticules sur la plate-forme. Le temps de vidange pour la plate-forme est estimé à quatre mois; le temps de séjour pour 90 à 95 % des macroparticules provenant du fleuve est d'environ 10 jours. Par conséquent, on prévoit que la plupart des métaux et des hydrocarbures provenant du fleuve se déposeront sur la plate-forme. Le dépôt atmosphérique et l'érosion côtière comptent pour moins de 5 % de l'écoulement naturel de métaux et d'hydrocarbures dans les secteurs concernés.

Les sources prévues d'origine humaine de métaux lourds et d'hydrocarbures déversés sur la plate-forme comprennent les fluides résiduels de forage, l'eau produite, les eaux usées et la combustion de carburant et de résidus; les fluides résiduels de forage constituent la source prédominante. Les estimations de l'écoulement d'apports d'origine humaine sont probablement établies au pire, étant donné que les prévisions de l'industrie pétrolière concernant la production de pétrole et le rythme de développement de la mer de Beaufort ont été rajustés à la baisse.

Sur une base régionale et compte tenu du taux de production prévue pour l'an 2000 (environ 203 000 m^3 de pétrole par jour), le rapport de l'écoulement d'origine humaine à l'écoulement naturel est évalué respectivement à 0.0023; 0.0023; 0.0038; 0.008; 0.009; 0.062; 0.063 et 3.3 pour le nickel, le cuivre, le cadmium, le chrome, le zinc, le mercure, le plomb et les hydrocarbures totaux.

Mots-clés:

mer de Beaufort, équilibre de masse géochimique, métaux lourds, hydrocarbures, éléments nutritifs, fleuve Mackenzie, macroparticules, eau de mer, dépôt atmosphérique, production de pétrole, boue de forage, eau produite, eaux usées, résidus.

ABSTRACT

D.J. Thomas, R.W. Macdonald and A.B. Cornford, 1983. A comparison of natural and petroleum resource development fluxes of metals, hydrocarbons and nitrogen, phosphorus and silicon to the Beaufort Sea. Can. Tech. Rep. Hydrogr. and Ocean Sci. 30: 48 pp.

A geochemical mass balance approach was used to compare the natural flux of heavy metals and hydrocarbons from the Mackenzie River to the Beaufort Sea with the projected anthropogenic flux of heavy metals and hydrocarbons from proposed hydrocarbon production activities on the Beaufort Sea Shelf. Time scales and geographical scales for pollutants specific to the Mackenzie River/Beaufort Sea estuarine zone were set. The geochemical mass balance is a useful first step toward estimating possible effects of industrial activity in the coastal zone; it is within the framework of the physico-chemical estuary that bioavailability, bioaccumulation and ultimately, biological effect can be addressed.

The natural inputs to the Beaufort Sea are dominated by the Mackenzie River which delivers about 3.7×10^{11} m^3 discharge and 8.7×10^7 m^3 particulates to the shelf each year. The flushing time for the shelf is estimated at four months; the residence time for 90-95% of the river-derived particulates is about 10 days. Consequently, most of the metals and hydrocarbons derived from the river are expected to settle out on the shelf. Atmospheric deposition and coastal erosion account for less than 5% of the natural flux of metals and hydrocarbons to the areas.

Projected anthropogenic sources of heavy metals and hydrocarbons to the shelf include waste drilling fluids, produced water, sewage and combustion of fuel and trash; waste drilling fluids are the predominant source. The estimates for the flux of anthropogenic inputs probably represent the "worst case" because oil industry projections for oil production and the pacing of Beaufort Sea Development have recently been adjusted downward.

On a regional basis and for the production rate projected for the year 2000 (approx. 203,000 m^3 oil per day), the ratio of anthropogenic to natural flux is estimated at 0.0023, 0.0023, 0.0038, 0.008, 0.009, 0.062, 0.063 and 3.3 for nickel, copper, cadmium, chromium, zinc, mercury, lead and total hydrocarbons, respectively.

This technical report is the first contribution to the appraisal phase of the Arctic data compilation and appraisal series, Canadian Data Report of Hydrography and Ocean Sciences No. 5. Volumes published to date in the series are indicated on the inside back cover of this report.

Key Words:

Beaufort Sea, geochemical mass balance, heavy metals, hydrocarbons, nutrient elements, Mackenzie River, particulates, sea water, atmospheric deposition, petroleum production, drilling mud, produced water, sewage, trash

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1. INTRODUCTION

The level of industrial activity in the Canadian Beaufort Sea related to the exploration for petroleum hydrocarbons has been increasing steadily during the past decade. Current development scenarios indicate a large expansion in activity during the remaining years of this century as the oil fields are brought into production and as the level of exploratory drilling increases.

The Beaufort Sea-Mackenzie River area is considered by many to be a pristine environment supporting an ecosystem which has only a poor capacity for assimilating industrial pollution. Consequently, a concern is often expressed as to the possible detrimental effects on the environment of mobilizing heavy metals, hydrocarbons and nutrients resulting from oil exploration and production activities. To date, the debate about such concerns has been, for the most part, qualitative. As a useful "first-order" evaluation of this concern, we have applied in this report, the "mass-balance" approach which involves comparing the expected anthropogenic flux of a particular chemical component for a given development scenario with the calculated natural flux for the same component within specified boundaries. The estimates for anthropogenic fluxes related to exploitation of Beaufort Sea petroleum resources are based on the scenarios described in ESSA (1980), Bercha (1979) and Montreal Engineering (1981). A more recent development scenario has been published since completion of this mass balance (Beaufort Sea Environmental Impact Statement, Dome Petroleum, 1982). This scenario indicates a lower level of development activity compared to the one used here. It is still valid, nonetheless, to consider the implications of this mass balance using the "old" scenario, because the higher estimates probably represent a "worst case" situation; in addition, it is conceivable that as Beaufort Sea development proceeds the higher estimates may be realised.

Anthropogenic pollutants in the environment may or may not have natural counterparts. Metals, nutrients and hydrocarbons clearly belong to the former group. Their occurrence and distribution are determined by fundamental natural cycles. Many halogenated hydrocarbons and fission-produced radionuclides, on the other hand, have no natural counterparts. For the elements or compounds with natural cycles, it is sensible to evaluate man's effect by comparing the magnitude of his contribution with that of nature. The scale for comparison depends on the chemical substance being examined together with the natural processes which balance its input and output. For example, the

scale of a single inlet or bay may be appropriate when considering a mercury problem but completely inappropriate when studying atmospheric CO_2 which is a global problem.

In this report, we have considered anthropogenic inputs of only those substances which occur naturally. Geographic boundaries have been set to a scale that seems intuitively appropriate. It should be noted, therefore, that this boundary is arbitrary and affects the magnitudes of the numbers listed in the tables. If the expected anthropogenic fluxes are insignificant compared to the natural fluxes, then the likelihood of demonstrable environmental damage resulting from man's activities can be considered remote within the limits of the boundary assumptions although significant local effects cannot be ruled out. If, on the other hand, the expected anthropogenic fluxes are found to rival natural fluxes then the possibility of serious damage to or alteration of the ecosystem within the limits of the boundary assumptions can be suspected. The problem should then be examined in greater detail to determine the probability of meaningful environmental consequence. It must be stressed that, although mass balance calculations can lead to a quantitative expression of the relative magnitude of natural and anthropogenic fluxes, conclusions of environmental consequences can be in error if - as discussed by Goldberg (1975) -there exists a "surprise factor". An example of a "surprise factor" is the methylation and subsequent bio-accumulation and bio-magnification of methylmercury. The mass balance approach, therefore, should not be used in isolation but rather as a first step in evaluating the effects (and their magnitude) anticipated from man's activities.

This report summarizes the results of mass balance calculations for the Mackenzie River Estuary/Beaufort Sea area carried out under the terms of DSS contract No. 04SB-FP833-1-0095.

2. STUDY OBJECTIVE

The specific objectives of this study were:

(1) to identify the major sources of heavy metals, hydrocarbons, nutrients and other chemical data for which a usable data base exists;

(2) to use the chemical data compiled under DSS contract No. 05SB.FP833-0-2715. (Thomas et al., 1982) as a basis for estimating the average Beaufort Sea concentrations of the chemical constituents referred to in (1) above;

(3) to estimate the residence times of chemical species using average Beaufort Sea concentrations and natural flux estimates;

(4) to compare natural fluxes and anticipated anthropogenic fluxes of the relevant chemical species for a particular development scenario during periods of maximum and minimum natural flux over the Beaufort shelf; and

(5) to compare the degree and nature of fluxes as outlined in (4) over a limited geographical scale; viz., the Tarsiut oil field.

3. BACKGROUND INFORMATION

3.1 The Study Area

The area used in the chemical mass-balance calculations which follow has been arbitrarily chosen as being that part of the Beaufort Sea from the Yukon/Alaska border to the entrance of the Amundsen Gulf (Cape Parry) out to the 200 m isobath (Figure 1). The analysis of oceanographic and satellite imagery data indicates this area to be strongly influenced by the suspended sediment load and freshwater output of the Mackenzie River. The location of all Beaufort Sea oil and gas exploration to date lies within the study area as does the expected location of future activity. The surface area of this region is approximately 60,000 km^2 with an average water depth of 42 m. The volume of water overlying the study area is therefore 2.5×10^{12} m^3. These and other data of a geographical nature are summarized in Table 1.

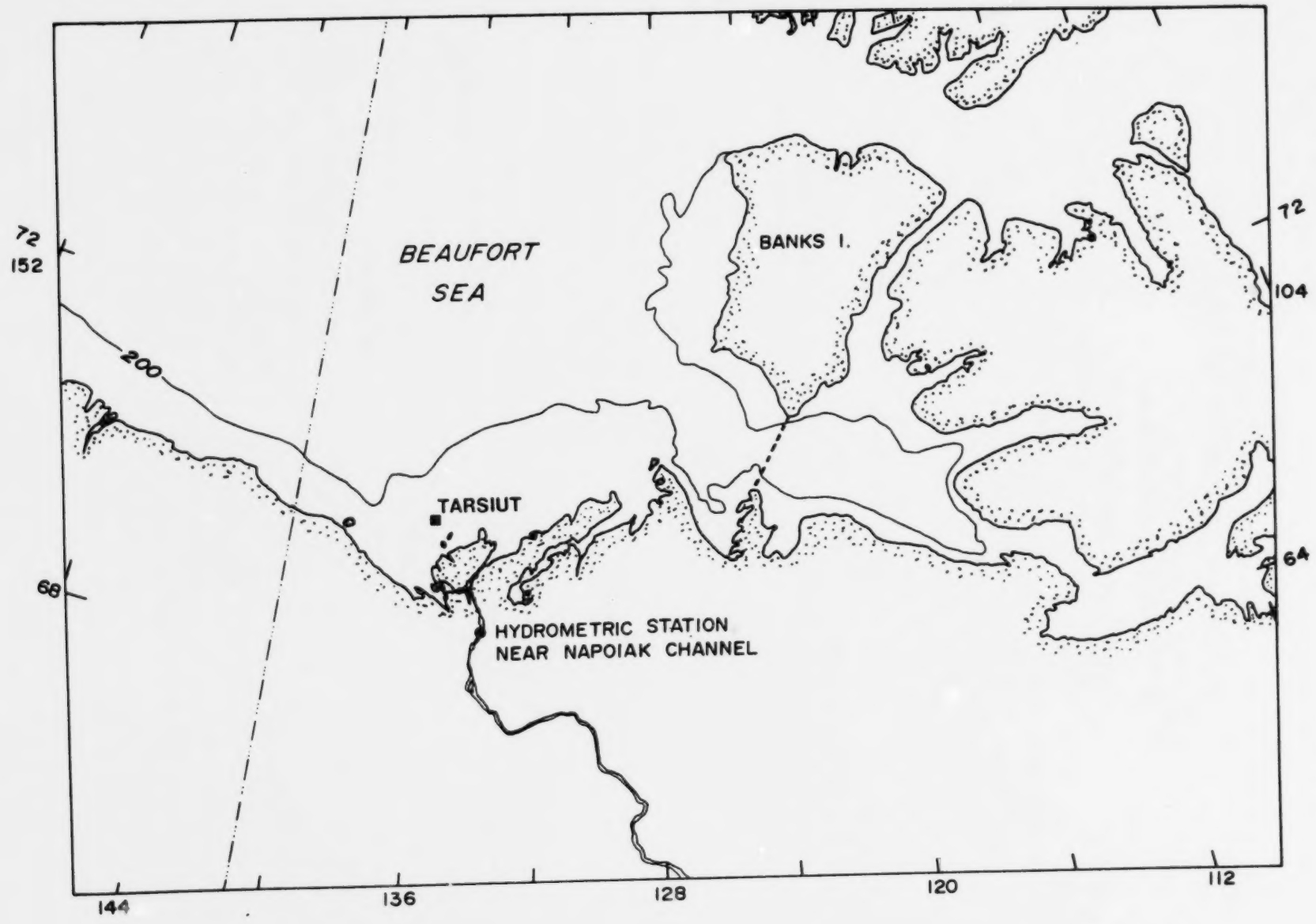


Figure 1. The area of the southern Beaufort Sea (shaded) to which the mass balance calculations apply.

TABLE 1

DATA USED TO ESTIMATE FLUXES

Annual River Discharge:	water	3.7×10^{11} m^3
	particulates	8.7×10^{7} m^3 (2.2×10^{11} kg)

Geographic boundaries of the receiving environment:

Yukon border to entrance to Amundsen Gulf (Cape Parry) out to 200 m isobath

average water depth:	42 m
surface area	approximately 60 000 km^2
volume	approximately 2.5×10^{12} m^3

The Beaufort Sea is an integral part of the Arctic Ocean and cannot be distinguished oceanographically. By imposing a boundary on the study area and allowing inputs into this area, an implicit assumption is made that the net mass flux across the boundary with the rest of the Arctic Ocean is zero. Residence times should be considered within this context. Substances with long residence times relative to the rate of exchange with Arctic waters are transported across the boundary, whereas substances with commensurate short residence times are deposited within the boundary. One way of estimating the residence time of fresh water within the estuarine system is to compare the input of freshwater and the "standing stock" of fresh water. Such a comparison has been made for two summers which represent extremes in the historical record: 1974, a "poor" ice year when ice remained close to shore for the duration of the open-water season, limiting the seaward transport of fresh water; and 1975, a "good" ice year when fresh water was free to mix with the receiving shelf waters and move out of the study area (see Section 4.2.2).

3.2 The Development Scenario

The mass balance calculations have been made for the level of activity expected in the years 1990 and 2000. The estimated levels of activity in the Beaufort for these years as shown in Table 2 are based on the development scenario outlined by ESSA (1980), Bercha (1979) and Montreal Engineering (1981).

3.3 Mass Transport to the Beaufort Sea

Possible natural agents of mass transport to the Beaufort Sea include:

(1) river runoff (water, dissolved components, suspended sediment, bedload);

(2) coastal erosion;

(3) wet and dry atmospheric deposition; and

(4) exchange with the Arctic Ocean.

TABLE 2.

DEVELOPMENT SCENARIO

HIGH PRODUCTION USING TANKERS[1]

	1990	2000
Production Rate (crude oil)	47 x 10^3 m^3 d^{-1}	203 x $10^3 m^3$ d^{-1}
Exploration wells (annual)	13	17
Production wells (annual)	23	52
Production Wells (cumulative)	91	556
Shallow Production Islands	2	0
Deep Production Islands	1	0.5
Exploration Island	6*	4
Arctic Production and Loading Atolls (APLAs)	0.33	0
Dredging Requirements **		
Shallow production islands	20 x 10^6 m^3	none
Deep production islands	40 x 10^6 m^3	10 x 10^6 m^3
Exploration Islands	18 x 10^6 m^3	12 x 10^6 m^3
APLAs (deep)	33 x 10^6 m^3	none
TOTAL	111 x 10^6 m^3	22 x 10^6 m^3
Personnel	5 000	25 000

1 ESSA, 1980

* Figure of 6 has been moved from 1989 to 1990 for the sake of a "worst case" argument.

** m^3, dry weight basis.

The Mackenzie River is the dominant influence in mass transport to the Beaufort Sea; It accounts for about 97% of the annual sediment flux. This is almost exclusively suspended load; bedload transport is considered small, probably no more than a few percent. Yukon rivers are not significant as agents of mass transport although they may be important in the immediate vicinities of their discharges. Coastal erosion which accounts for at most 3% of the sediment input into the Beaufort Sea, is therefore of far less importance than that of the Mackenzie River (Harper and Penland, 1982). Calculations given below show that atmospheric deposition is of limited importance to the overall transport of particulates to the Beaufort Sea (see Table 6).

Mass Transport by the Mackenzie River

Estimates for the input of freshwater and suspended particulates to the Beaufort Sea are based on hydrometric data reported for the station located in the Middle Channel of the Mackenzie River above Napoiak Channel (68° 26' 00" N; 134° 06' 50" W, see Figure 1). Data for discharge, suspended particulate matter (SPM) flux and calculated sedimentation rates are given in Table 3.

The discharge data have been multiplied by a factor of 1.11 to reflect the fact that, on an annual average basis, only 90% of the water entering the delta flows through the Middle Channel (Davies, 1975). No correction has been applied to the discharge data, however, to account for the apparent increase by up to 15% of the waters entering the Beaufort Sea compared to those entering the delta (presumably the difference is groundwater additions within the delta). The table entries for river discharge between January and May are an average of the mean flow for 1975 and 1976 (Water Survey of Canada, 1980). The data have been assembled in this fashion because no measurements were made of flow or suspended load during the first five months of 1974. The remaining 1974 data are the only available set which includes direct measurements of suspended sediments. This leads to an estimate for the total annual discharge of the Mackenzie River of 3.7×10^{11} m^3 with a daily average of 11 540 m^3/sec. Reeder et al. (1972) estimated the flow at 9630 m^3/sec and Davies (1975) suggested a value of greater than 8500 m^3/sec. Both these estimates, however, are probably underestimates because they do not account for that part of the Mackenzie River discharge which has a source within the Delta.

TABLE 3

ESTIMATED RIVER WATER AND SUSPENDED SEDIMENT FLUXES TO THE BEAUFORT SEA[1]

MONTH	DISCHARGE		SPM FLUX (NOTE 3)				SEDIMENTATION RATE ON BEAUFORT SEA SHELF (NOTE 4)			
	AVERAGE DAILY (m^3/s) (NOTE 2)	MONTHLY TOTAL ($m^3 \times 10^{-9}$)	TONNES/d (m^3/d)		TONNES/month (m^3/month)		A. cm/month (g/m^2/month)		B. cm/month (g/m^2/month)	
JANUARY	4 525	12.1	766	E (306)	23 750	(9 490)	0.00012	(1.19)	0.000024	(0.24)
FEBRUARY	4 270	10.3	766	E (306)	21 450	(8 570)	0.00011	(1.08)	0.000022	(0.22)
MARCH	3 900	10.4	672	E (269)	20 830	(8 340)	0.00010	(1.04)	0.000021	(0.21)
APRIL	3 610	9.4	614	E (245)	18 420	(7 350)	0.00009	(0.92)	0.000018	(0.18)
MAY	16 260	43.6	244 200	E (97 680)	7 570 200	(3 028 080)	0.038	(379)	0.0076	(76)
JUNE	21 200	54.9	2 697 300	E (1 078 920)	80 919 000	(32 367 600)	0.40	(4 046)	0.08	(809)
JULY	19 650	52.6	1 560 660	(624 260)	48 380 460	(19 352 060)	0.24	(2 419)	0.05	(484)
AUGUST	20 760	55.6	2 283 490	(913 530)	70 850 190	(28 319 430)	0.35	(3 543)	0.07	(709)
SEPTEMBER	15 540	40.3	227 550	(91 020)	6 826 500	(2 730 600)	0.034	(341)	0.0068	(68)
OCTOBER	11 880	31.9	66 600	E (26 640)	2 064 600	(825 840)	0.010	(103)	0.002	(21)
NOVEMBER	10 435	27.1	44 400	E (17 760)	1 332 000	(532 800)	0.0067	(67)	0.0013	(13)
DECEMBER	6 440	[illegible].3	1 110	E (444)	34 410	(13 760)	0.00017	(1.72)	0.000034	(0.34)
ANNUAL TOTAL	-	365.5	-	-	218 061 810	(87 203 920)	1.08	(10 904)	0.22	(2 181)
ANNUAL MEAN	11 540	30.5	-	-	-	-	-	-	-	-
% during ice-free conditions (June - September)	56%		95%				95%			
% during ice cover conditions (October - May)	44%		5%				5%			

Note 1. Calculations based on hydrometric data for Mackenzie River (Middle Channel) above Napoiak Channel (68° 26' 00" N; 134° 06' 50" W). Published data scaled by a factor of 1.11 to account for contributions of other river channels.

Note 2. January to May data are an average of mean data for 1975, 1976 (Water Survey of Canada, 1980); June to December data are from 1974 (Water Survey of Canada, 1980).

Note 3. Conversion from tonnes/d to m^3/d assumes average sediment specific gravity value of 2.5.

Note 4. Sedimentation rate data presented for 2 shelf areas: A - the area shoreward of the 10 m isobath; B - the area between 10 m and 200 m isobath. Calculations based on the following assumptions: (i) 50% of total particulate flux is deposited evenly over delta front and continental shelf shoreward of the 10 m isobath (10,000 km^2) (ii) remainder of sediment is deposited evenly over the area between the 10 m and 200 m isobaths (50,000 km^2) (iii) porosity of the deposited sediments is 60%.

E. Estimated particulate flux (see text); values for July, August and September from Davies (1975).

The estimation of a total annual particulate flux for the river is difficult because no direct measurements of concentrations are available for the period October to June. Furthermore, where data do exist, large errors may be suspected because daily particulate fluxes are usually estimated by multiplying the concentration of suspended particulate matter from a very small number of samples at one station by the total daily flow rate. The estimated values for particulate fluxes appearing in Table 3 were obtained by inspection of all the daily discharge data for stations along the Mackenzie and its tributaries close to the Middle Channel station above Napoiak Channel. This led to the determination of average suspended sediment concentrations as a function of the discharge rate. Suspended sediment concentrations obtained in this manner were then used to generate particulate fluxes at the Middle Channel station. The particulate flux was estimated for uncorrected discharge values, then multiplied by 1.11 to account for transport by river channels in addition to the Middle Channel; the calculated particulate flux leads to an average suspended sediment concentration for the Mackenzie River that is within 10% of the global average of river suspended sediment as reported by Li (1981) and shown below:

Li (1981)

Total suspended particulate flux from rivers to the oceans	= $(18 \pm 3) \times 10^{15}$ g a^{-1} *
Total freshwater supply to oceans	= $(33 \pm 3) \times 10^{18}$ g a^{-1}
Therefore, average suspended sediments	= 545 g m^{-3}

This Study

Total annual suspended solids	= 2.2×10^{14} g a^{-1}
Total annual flow Mackenzie River	= 3.7×10^{11} m^3 a^{-1}
Therefore, average suspended sediments, Mackenzie River	= 595 g m^{-3}

* SI unit for year is a (=annum)

Several problems are inherent in this method of estimating particulate fluxes. The underlying assumption that flow characteristics at all the river and tributary stations were similar is certainly incorrect but the error resulting from the assumption is difficult to quantify. Hysteresis* is also a serious problem because it leads to an almost unpredictable relationship between flow and suspended load (Whitfield, 1981; McLaren, 1981). It is expected, however, that the error in estimating annual particulate flux as the result of hysteresis will be no greater than 45% assuming an error of 100% in estimating monthly particulate fluxes during the period October to June when no direct measurements are available. An alternative for estimating the particulate flux was attempted which involved using the exponential equation relating instantaneous suspended sediment concentrations and instantaneous discharge described by Brunskill et al., (1975). The method was not pursued after it failed to reproduce test data satisfactorily.

The total annual particulate flux estimated by the method described above is approximately 2.2×10^8 tonnes. This agrees closely with a recent estimate made independently by Woodward-Clyde Inc. in conjunction with a study of sediment dynamics on the Beaufort Sea Shelf (Harper and Penland, 1982); on the other hand, Milliman and Meade (1983) suggest that a realistic estimate may be 1.0×10^8 tonnes a^{-1}. It is interesting to note that, while 95% of the annual sediment transport by the river occurs during the ice-free season, only 56% of the total annual river discharge occurs during the same period (Table 3).

The sedimentation rate over the Beaufort Shelf region varies and tends to decrease with distance away from the delta. An estimate of monthly sedimentation rates, therefore, is shown for two zones: one shoreward of the 10 m isobath and the other between the 10 m and 200 m isobaths (see Table 3). The average annual sedimentation rates are 1.08 cm and 0.22 cm for each zone respectively. These calculations are made on the assumption that no sediment escapes the study area, that 50% of river sediment is deposited shoreward of the 10 m isobath, that the sedimentation is uniform; and that the porosity of the deposited sediments is 60%. As such, the calculated values probably represent maximum average rates of sediment accumulation. Radiochemical dating indicates that during the past 8000 years an average 8 m of sediment has been laid down on the Beaufort Sea Shelf (S. Blasco, personal

* Hysteresis is the lagging of an effect behind its cause; in this case, if suspended sediment concentration is plotted against river discharge in the time sequence of occurrence, a loop is formed.

communication). This corresponds to an average sedimentation rate of approximately 0.1 cm a^{-1} (assuming an average porosity of 0.6).

One strong characteristic of the river discharge and sedimentation pattern is the high seasonal variation. Maximum water discharge is approximately six times the minimum. The rate of particulate transport is about 4400 times greater at freshet than at low flow. Estimated sedimentation rates range from 0.00009 to 0.40 cm/month and 0.000018 and 0.08 cm/month for the areas shoreward of the 10 m isobath and between the 10 and 200 m isobaths respectively. By contrast, using data for the past 12 years, year-to-year variations of $\pm$ 30% in these quantities would be considered large. Thus, the short-term seasonal changes are very much greater than year to year variability.

4. THE MASS-BALANCE

4.1 Chemical Parameters Included

Although a large amount of data was identified in the previous Beaufort Sea chemical data compilation study (Thomas et al., 1982), much was considered unreliable due to methods used for sample collection, storage and preservation which are now considered to lead to erroneous results. The chemical parameters included in the mass balance discussed below are:

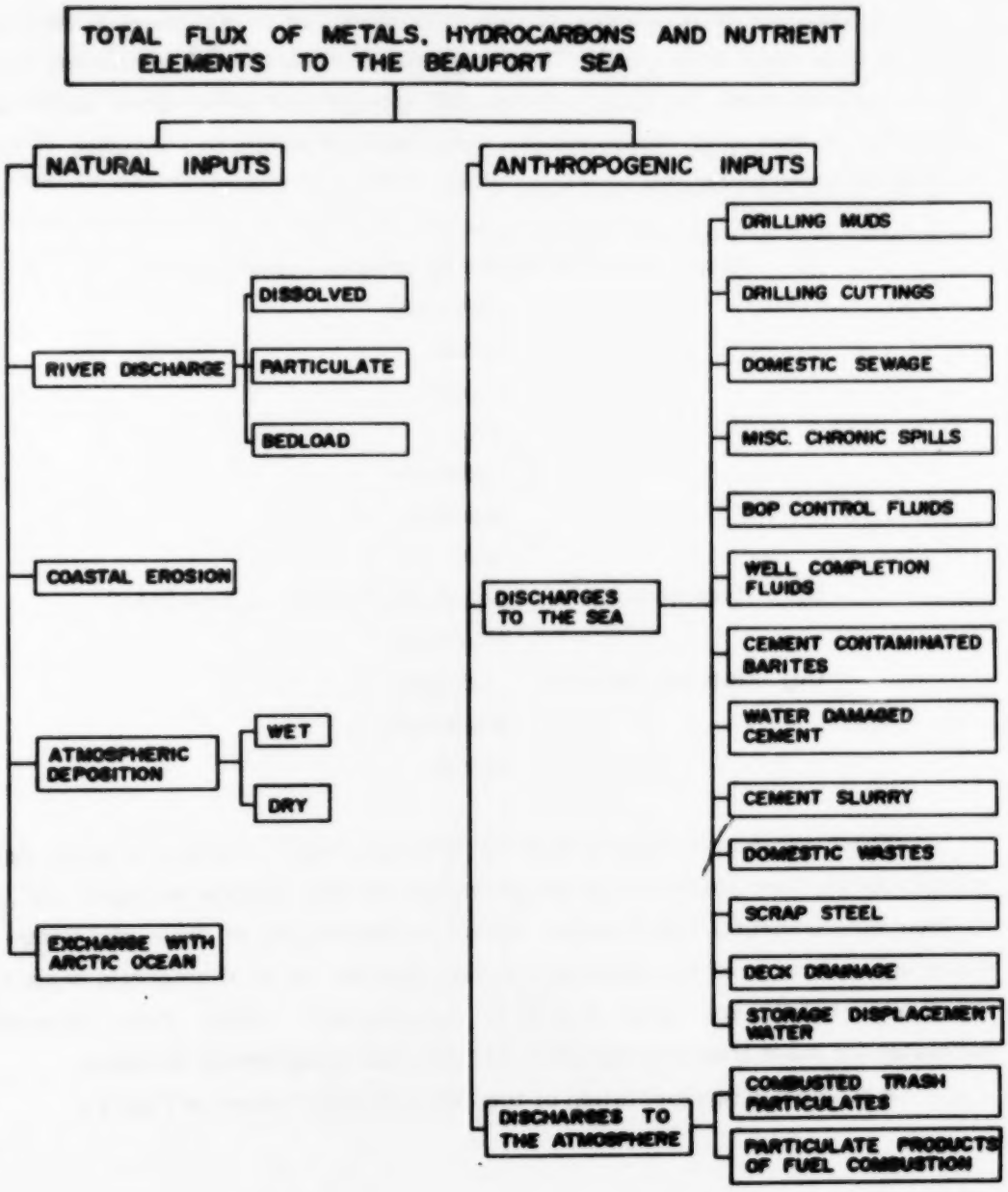
(i)	Heavy metals (in ascending order of atomic weight)	chromium
		nickel
		copper
		zinc
		cadmium
		mercury
		lead
(ii)	Hydrocarbons	polyaromatic hydrocarbons (PAH)
		n-alkanes
(iii)	Nutrient elements	nitrogen
		phosphorus
		silicon

These parameters were chosen for the mass balance because a usable data base is available for them (in the estuarine system) in the data compilation report and because of their environmental significance. Direct measurements of these parameters in the water and sediments of the Mackenzie River, however, or in atmospheric deposition for the Beaufort Sea, are often scarce or non-existent. Under these circumstances, estimates are made from the available data for other geographical locations.

A schematic representation of the mass balance is shown in Figure 2.

Figure 2.

Schematic Representation of the Mass Balance



4.2 Natural Fluxes

As outlined above, the predominant inputs to the Beaufort Sea are associated with the dissolved and particulate river discharge. Atmospheric deposition is probably the most significant source of the elements included in this mass balance after dissolved and particulate river discharge; the contributions from atmospheric deposition, however, are usually less than 1% to a few percent of total river inputs (see Table 6).

4.2.1 River Inputs

Estimates of the dissolved and particulate fluxes of heavy metals, hydrocarbons and nutrient elements from Mackenzie River discharge are given in Table 4. Unfortunately, there is no large data base giving the concentrations of these components in Mackenzie River water. Values for Cr, Cu, Zn, Cd, Pb and Hg are based on direct measurements of river water and particulates at stations within the Mackenzie Delta; they are within the ranges observed in other rivers. Because no data for particulate Ni could be found for river sediment within the Mackenzie delta, concentrations commonly found in nearshore Beaufort Sea sediments were substituted*. Dissolved nutrient concentrations represent measurements performed on delta river water but particulate nutrient concentrations had to be estimated by extrapolating data obtained outside the delta.

The estimates for the river input of hydrocarbons to the Beaufort Sea pose the greatest problem because there is no data base upon which to fix the calculations. This is unfortunate because the flux of hydrocarbons to the Beaufort Sea is most relevant to the exploration for offshore oil and gas reserves. Various compromises were made in computing hydrocarbon fluxes. For example, Beaufort Sea sediment values were used to approximate the concentration of PAH in river particulates; Beaufort Sea dissolved PAH vs salinity data were extrapolated to zero salinity to estimate dissolved PAH in river water; and dissolved n-alkane concentrations from Alaskan waters were used. The influence of these approximations on the magnitude of the calculated fluxes is unknown.

* This substitution appears to be reasonable. The concentrations of Cr, Cu, Zn, Cd, Pb and Hg for nearshore (Thomas et al., 1982) and Mackenzie River Sediment (Brunskill et al., 1977) generally fall within the same ranges. Local differences can occur; these are usually related to sediment grain size.

TABLE 4.

ESTIMATES OF ANNUAL INPUTS TO THE BEAUFORT SEA: RIVER INPUT

PARAMETER	PARTICULATE FLUX			DISSOLVED FLUX		
	AVERAGE CONCENTRATION RANGE	REF.	ANNUAL FLUX (mol)	AVERAGE CONCENTRATION	REF.	ANNUAL FLUX (mol)
Cr	0.14 - 0.16 (μmol/g)	1	$(3.1 - 3.5) \times 10^7$	8.9×10^{-5} mol m-3	2	3.3×10^7
Ni	1.02 - 1.70 (μmol/g)	10	$(22 - 37) \times 10^7$	1.7×10^{-5} mol m-3	2	6.3×10^6
Cu	0.36 - 0.66 (μmol/g)	1	$(7.8 - 14.3) \times 10^7$	7.9×10^{-5} mol m-3	2	2.9×10^7
Zn	1.71 - 1.93 (μmol/g)	1	$(37 - 41) \times 10^7$	4.6×10^{-5} mol m-3	2	1.7×10^7
Cd	7.2 - 46.3 (nmol/g)	1	$(1.6 - 10.0) \times 10^6$	8.9×10^{-6} mol m-3	2	3.3×10^6
Hg	0.25 - 0.50 (nmol/g)	11	$(5.5 - 11) \times 10^4$	2.5×10^{-8} mol m-3	2	9.3×10^4
Pb	12.1 - 116 (nmol/g)	1	$(2.7 - 25.5) \times 10^6$	9.7×10^{-6} mol m-3	2	3.6×10^6
PAH	0.2 - 2.8 (μg/g)	7	3.1×10^5 kg	56 ng/L	8	2.1×10^4 kg
n-alkanes	5.8 (μg/g)	3	1.4×10^6 kg	0.3 μg/L	9	1.1×10^5 kg
N	0.1 (mol/m^3)	5	4.13×10^{10}	2×10^{-2} mol m-3	(4,2)	7.4×10^9
P	0.014 (mol/m^3)	5	5.78×10^9	5×10^{-4} mol m-3	(4,2)	1.9×10^8
Si	0.01 (mol/m^3)	6	2.46×10^{12}	1.4×10^{-1} mol m-3	(4,2)	5.2×10^{10}

1. Wagemann et al., 1977.
2. Environment Canada 1981.
3. Peake et al., 1972.
4. Reeder et al., 1972.
5. Brunskill et al., 1975.
6. Estimated from data in ref. 5 above relating Si concentrations in river water of the same watershed.
7. Estimated average from Beaufort Sea surface sediment as reported in Wong et al. 1976.
8. Estimated by extrapolating plot of PAH vs salinity (page 74) to zero salinity.
9. Shaw and Baker 1978.
10. Estimated from concentrations observed in nearshore Beaufort Sea Sediment.
11. Arctic Laboratories Limited, 1982. Unpublished results for total mercury in East Channel Mackenzie River water, July 1982.

Because direct measurements of hydrocarbon concentrations on river particulates and water were lacking, a number of approaches were considered to calculate river-borne hydrocarbon inputs to the Beaufort Sea indirectly. For example, many hydrocarbon seeps occur along the river; if the composite volume of annual seepage were known together with the abundance of aliphatic and aromatic hydrocarbons in the seep fluids, then a flux could be calculated. Alternatively, nickel and vanadium porphyrins could be used as tracers of the seeps in river water. By knowing the concentrations of these porphyrins in both seep material and river water a flux could be calculated. Unfortunately, none of these data exist, nor are there current or planned research programs associated with the Mackenzie River basin that could fill these data gaps (E. Peake, personal communication). The use of metal porphyrins as tracers appears to be worthy of consideration.

4.2.2 Atmospheric Deposition

There are no direct measurements of wet or dry atmospheric deposition for the Beaufort Sea. Table 5 was constructed using the average published values for atmospheric deposition in non-industrial or remote geographical areas.

4.2.3 Mean Residence Time

The mean residence time of an element in the sea is defined as the ratio,

$$\frac{\text{total mass of an element in the sea}}{\text{mass supplied per unit time (year)}}$$

This is a useful concept because it gives a measure of the "memory" or recovery time of an area following a significant environmental impact. The calculated mean residence times for heavy metals, hydrocarbons and nutrient elements are shown in Table 6. For heavy metals, hydrocarbons and nutrients, the residence times are generally in the order of months. Assuming the box model approximation of the study area, the maximum residence (replacement) time of water on the shelf would be about six years (volume over shelf/annual freshwater input). The estimate of a six year residence time for shelf

TABLE 5

ESTIMATES OF ANNUAL INPUTS TO THE BEAUFORT SEA:

ATMOSPHERIC INPUT

PARAMETER	DEPOSITION (wet & dry) mol km^{-2} a^{-1}	REF.	TOTAL FLUX. mol a^{-1}
Cr	3.9	1	23.4×10^4
Ni	17	2	102×10^4
Cu	126	3	756×10^4
Zn	459	4	2754×10^4
Cd	5.3	5	31.8×10^4
Hg	0.05	6	3×10^3
Pb	1	1	6×10^4
PAH	?		-
n-alkanes	?		-
N	7100	7,6	4.26×10^8
P	129	7	7.74×10^6
Si	5000	8	3.0×10^9

1. Estimated from rainfall using data of Tanner et al., 1972 and annual rainfall for Beaufort Sea of 20 cm/year (Burns, 1973).
2. Schmidt and Andren, 1980.
3. Nriagu and Davidson, 1980.
4. Nriagu and Davidson, 1980.
5. Nriagu, 1980.
6. Cawse, 1980.
7. Yadav and Mishra, 1979.
8. Subranmanian and Saxena, 1980.

TABLE 6.

NATURAL INPUTS INTO THE BEAUFORT SEA

CHEMICAL PARAMETER		MACKENZIE RIVER (DISSOLVED + PARTICULATE LOAD)			ATMOSPHERIC (WET + DRY)	TOTAL INPUTS	TOTAL CONTENT OF SHELF WATERS TO 200 m	BEAUFORT SEA RESIDENCE TIME (YEARS)
	Unit	Dissolved	Particulate	River Total				
Cr	(mol)	3.3×10^7	$(3.1 - 3.5) \times 10^7$	$(6.4 - 6.8) \times 10^7$	0.023×10^7	$(6.4 - 6.8) \times 10^7$	$(1.5 - 7.5) \times 10^6$	0.02 - 0.12
Ni	(mol)	6.3×10^6	$(22 - 37) \times 10^7$	$(23 - 38) \times 10^7$	0.10×10^7	$(23 - 38) \times 10^7$	$(12.5 - 42.5) \times 10^6$	0.05 - 0.19
Cu	(mol)	2.9×10^7	$(7.8 - 14.3) \times 10^7$	$(10.7 - 17.2) \times 10^7$	0.8×10^7	$(11.5 - 18.0) \times 10^7$	$(12.5 - 42.5) \times 10^6$	0.07 - 0.37
Zn	(mol)	1.7×10^7	$(37 - 41) \times 10^7$	$(39 - 43) \times 10^7$	2.8×10^7	$(42 - 46) \times 10^7$	$(8.8 - 35.0) \times 10^6$	0.02 - 0.08
Cd	(mol)	3.3×10^6	$(1.6 - 10.0) \times 10^6$	$(4.9 - 13.3) \times 10^6$	0.3×10^6	$(5.2 - 13.6) \times 10^6$	$(0.5 - 1.8) \times 10^6$	0.04 - 0.35
Hg	(mol)	9.3×10^4	$(5.5 - 11) \times 10^4$	$(14.8 - 20.3) \times 10^4$	0.3×10^4	$(15.1 - 20.6) \times 10^4$	$(0.05 - 0.25) \times 10^6$	0.2 - 1.4
Pb	(mol)	3.6×10^6	$(2.7 - 25.5) \times 10^6$	$(6.3 - 29.1) \times 10^6$	0.06×10^6	$(6.4 - 29.2) \times 10^6$	$(0.25 - 0.48) \times 10^6$	0.01 - 0.08
PAH	(kg)	2.1×10^4	$(0.4 - 6.2) \times 10^5$	$(0.6 - 6.4) \times 10^5$	probably insignificant	$(0.6 - 6.4) \times 10^5$	$(3.5 - 11.3) \times 10^4$	0.05 - 1.9
n-alkane	(kg)	1.1×10^5	1.4×10^6	1.5×10^6	probably insignificant	1.5×10^6	7.5×10^5	0.5
Total hydrocarbons	(kg)			(est) 1.8×10^7 (Note 1)	-	(est) 1.8×10^7 (Note 1)		
N	(mol)	7.4×10^9	4.1×10^{10}	4.8×10^{10}	0.04×10^{10}	4.8×10^{10}	1×10^{10}	0.21
P	(mol)	1.9×10^8	5.8×10^9	6.0×10^9	0.008×10^9	6.0×10^9	3×10^9	0.5
Si	(mol)	5.2×10^{10}	2.5×10^{12}	2.6×10^{12}	0.003×10^{12}	2.6×10^{12}	3.3×10^{10}	0.013

Note 1. Total hydrocarbons have been estimated at one order of magnitude greater than the sum of PAH and n-alkane inputs. This is approximate and based on (1) GC results that often show an unresolved complex mixture corresponding to up to 10 times more hydrocarbons than represented by quantified peaks and (2) gravimetric results which also exceed the n-alkane and PAH fractions by about a factor of 10 (Arctic Laboratories Limited, unpublished data).

waters is an upper limit value and clearly not realistic because advection across the boundaries of the study area occurs; consequently, the residence time of water on the shelf is expected to be shorter than six years.

An analysis of salinity profile data for 1974 and 1975 illustrates the point. The salinity measurements reported by Herlinveaux et al., (1976) were used to calculate the equivalent depth of freshwater which was present within the study area during Summer 1974, Spring 1975 and Summer 1975. This total amount of freshwater in the water column at each station was obtained by calculating the amount of freshwater required to dilute seawater having a salinity of 32.8°/oo (the maximum salinity in the data set) to the observed value at each depth in the profile and integrating over the entire water column (see Figures 3-7). The total amount of freshwater within the study area at a particular time was obtained by combining the freshwater contributions from each of 4 sectors of known area. The freshwater depth for each sector was taken as the average of freshwater depths for all stations within each sector. A summary of the calculated values is shown below.

	Volume of Freshwater	Equivalent Freshwater Depth
Summer 1974	61.3×10^{10} m^3	10.2 m
Spring 1975	35.0×10^{10} m^3	5.8 m
Summer 1975	52.6×10^{10} m^3	8.8 m
Residual	21.3×10^{10} m^3	3.6 m
Ice	10.8×10^{10} m^3	1.8 m
Rainfall	1.2×10^{10} m^3	0.2 m
Average Annual Runoff	37×10^{10} m^3	6.2 m

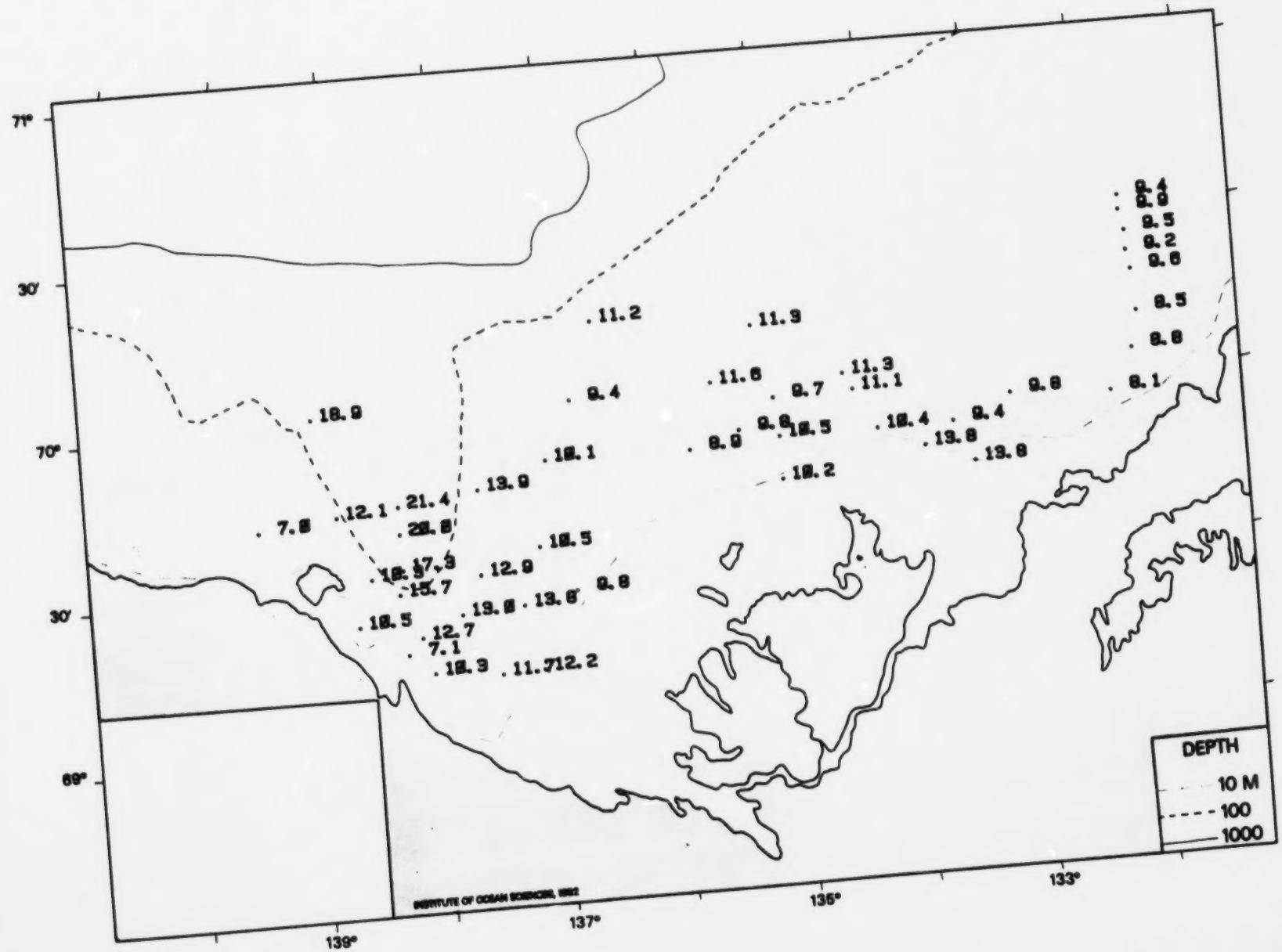
Residual freshwater is taken as the minimum amount of freshwater in the water column. This occurs approximately during late October when convective mixing creates an isohaline (30°/oo used for calculation) water column in shallow waters (<100 m) of the shelf just before freeze-up. Saline water also moves onto the shelf during this time. The calculations indicate internal consistency of the data. The value of 35.0×10^{10} m^3 for freshwater "standing crop" during Spring 1975 can be accounted for as the residual amount (21.3×10^{10} m^3) plus the cumulative Mackenzie River discharge for the period November to mid-May (10.8×10^{10} m^3). In addition, the difference in the calculated

freshwater content of the study area between the Spring 1975 and Summer 1975 measurement periods was 17.6×10^{10} m^3. During the same period of time approximately 28.8×10^{10} m^3 freshwater was added to the water column (10.8×10^{10} m^3 from ice-melt and 18.0×10^{10} m^3 from river discharge). These numbers suggest that there was a net movement of 11.2×10^{10} m^3 freshwater out of the study area. (This amounts to about 60% of the incoming river water.) The return to near-background salinity values each freeze-up and movement of large volumes of water out of the estuary indicate a residence time for freshwater on the shelf of months; this is consistent with the calculated residence times for chemical constituents of the shelf, the longest of which (except for Hg) is 6 months (see Table 6).

A comparison of the amount of freshwater present on the shelf during Summer 1974 and Summer 1975 provides an estimate for annual extremes. In 1974 ice remained close to shore for the duration of the open water season, limiting the seaward transport of freshwater; in 1975 the ice remained far offshore and the freshwater was free to mix with the receiving shelf waters and move offshore. Thus, in 1974 there was 16% (8.7×10^{10} m^3) more freshwater on the shelf than in 1975.

The total heavy metal, hydrocarbon and nutrient contents of the shelf waters used in the estimation of residence times were obtained using the values for shelf water concentrations as indicated in Table 7. The selection of representative background concentrations for heavy metals is almost always controversial because of the trend in recent years for reported metal values to decline following improvements in analytical methodology and the reduction and control of sample contamination. The values used here are reasonable for a coastal/estuarine area. They are not as low as some values which have been reported for open ocean background, but the concentrations used for Cd, Cu and Ni are similar to the open ocean values for these elements reported by Danielsson (1980).

Figure 3. Equivalent depths (in metres) of freshwater in the southern Beaufort Sea during the summer of 1974. Each value for equivalent depth has been estimated from the salinity profile data reported in Herlinveaux et al., 1976.


71°
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DEPTH
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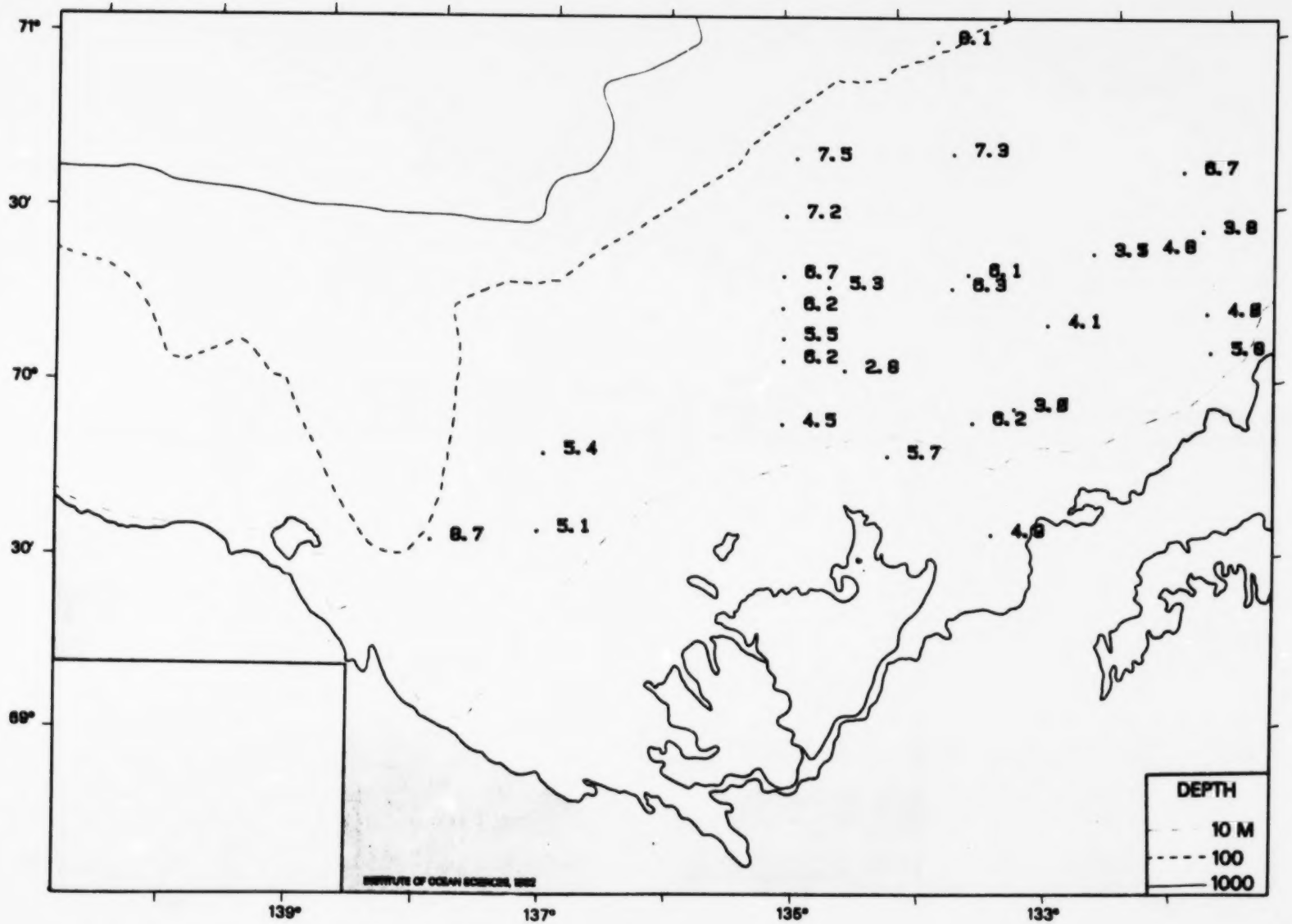
INSTITUTE OF OCEAN SCIENCES, 1982

Figure 4. Equivalent depths (in metres) of freshwater in the southern Beaufort Sea during the spring of 1975. Each value for equivalent depth has been estimated from the salinity profile data reported in Herlinveaux et al., 1976.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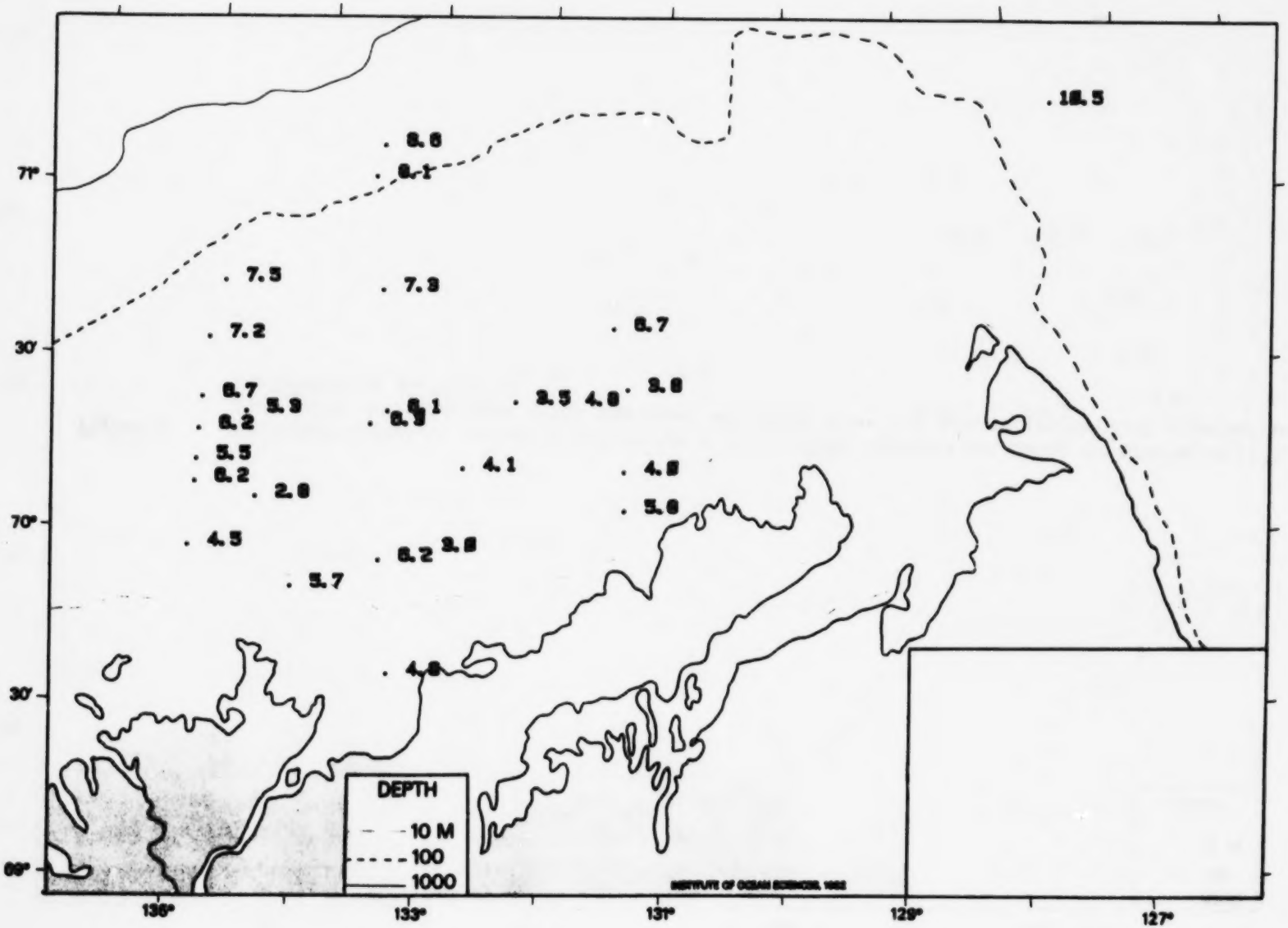
INSTITUTE OF OCEAN SCIENCES, 1982

Figure 5. Equivalent depths (in metres) of freshwater in the Southern Beaufort Sea (adjacent to the area shown in Figure 3) during the spring of 1975. Each value for equivalent depth has been estimated from the salinity profile data reported in Herlinveaux et al., 1976.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71°
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30'
30'
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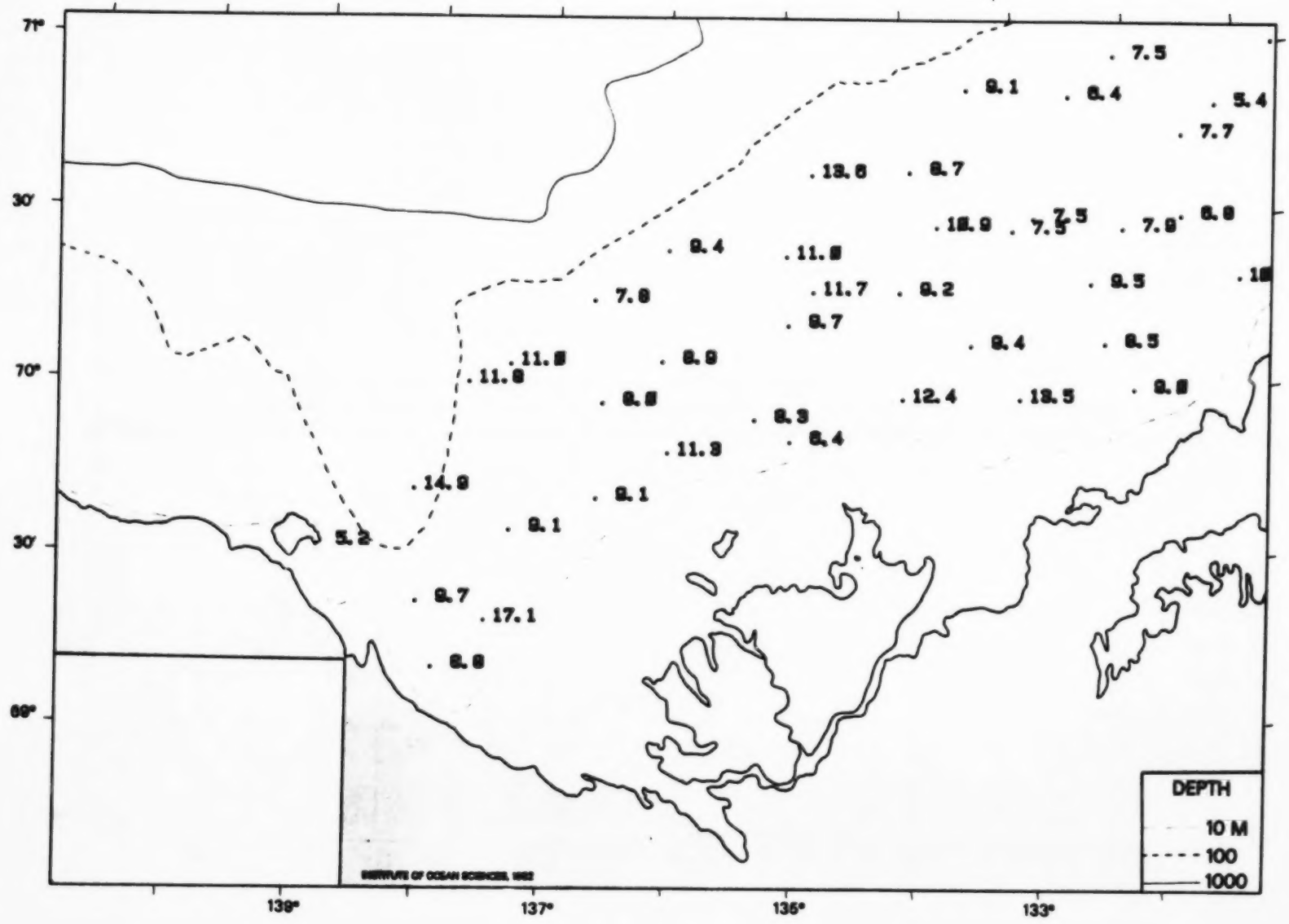
131°
129°
127°
DEPTH
10 M
100
1000

Figure 6. Equivalent depths (in metres) of freshwater in the southern Beaufort Sea during the summer of 1975. Each value for equivalent depth has been estimated from the salinity profile data reported in Herlinveaux et al., 1976.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9.7
17.1
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DEPTH
10 M
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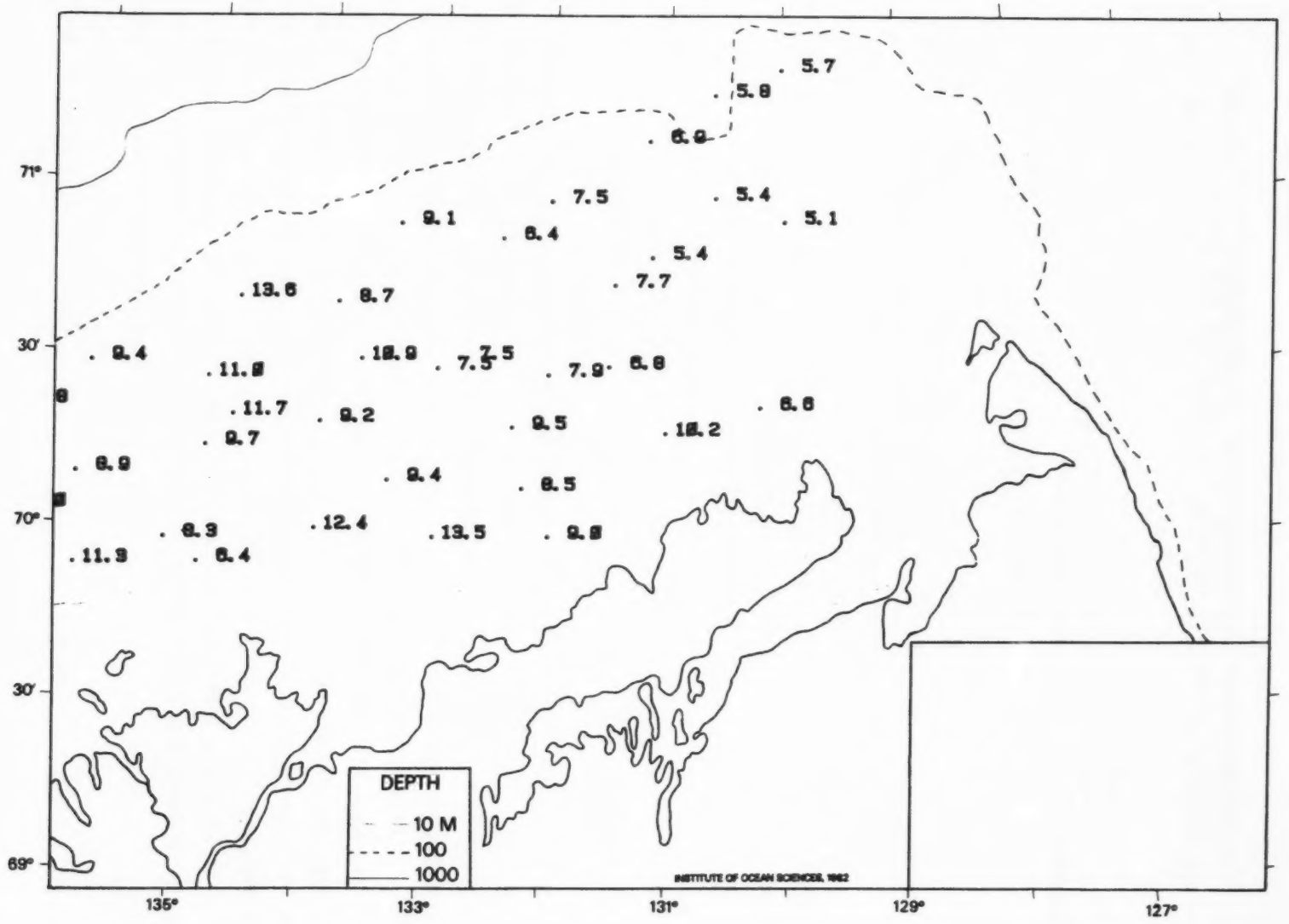
INSTITUTE OF OCEAN SCIENCES, 1982

Figure 7. Equivalent depths (in metres) of freshwater in the southern Beaufort Sea (adjacent to the area shown in Figure 5) during the summer of 1975. Each value for equivalent depth has been estimated from the salinity profile data reported in Herlinveaux et al., 1976.


5.7
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DEPTH
10 M
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INSTITUTE OF OCEAN SCIENCES, 1982

TABLE 7.

ESTIMATES OF TOTAL WATER BURDEN OF SELECTED CHEMICAL SUBSTANCES OVER THE BEAUFORT SEA SHELF

Parameter	Average Beaufort Sea Concentration Note 1		Total Burden Shelf Waters Note 2	
Cr	(0.6-3)	$\mu mol/m^3$	(1.5-7.5)	x 10^6 mol
Ni	(5-17)	$\mu mol/m^3$	(12.5-42.5)	x 10^6 mol
Cu	(5-17)	$\mu mol/m^3$	(12.5-42.5)	x 10^6 mol
Zn	(3.5-14)	$\mu mol/m^3$	(8.8-35.0)	x 10^6 mol
Cd	(0.2-0.7)	$\mu mol/m^3$	(0.5-1.8)	x 10^6 mol
Hg	(0.02-0.1)	$\mu mol/m^3$	(0.05-0.25)	x 10^6 mol
Pb	(0.10-0.19)	$\mu mol/m^3$	(0.25-0.48)	x 10^6 mol
PAH	(14-45)	ng/L	(3.5-11.3)	x 10^4 kg
n -alkanes	0.3	g/L	7.5	x 10^5 kg
N	4	$mmol/m^3$	1	x 10^{10} mol
P	1.2	$mmol/m^3$	3	x 10^9 mol
Si	13	$mmol/m^3$	3.3	x 10^{10} mol

Note 1. Thomas et al., 1982

Note 2. to the 200 m isobath

4.3 Anthropogenic Fluxes

Among the many possible inputs to the Beaufort Sea associated with the exploration for, and development of, offshore petroleum resources are the following:

(1) drilling fluids/drill cuttings;
(2) cement contaminated barites;
(3) water damaged cement;
(4) blow-out preventer (BOP) control fluids;
(5) well completion fluids;
(6) formation (produced) water;
(7) miscellaneous accidental hydrocarbon spills e.g., crude, diesel fuels, aviation fuel, lubricating oils, bilge water discharge, etc.;
(8) cement slurry;
(9) combustible trash;
(10) trash particulates;
(11) particulate products of fuel combustion;
(12) sanitary wastes (sewage);
(13) domestic wastes (grey water);
(14) scrap steel;
(15) deck drainage; and
(16) storage displacement water.

For the purpose of the chemical mass-balance calculations, only drilling fluids, domestic sewage, combustible trash, combustion of hydrocarbon fuels and miscellaneous chronic hydrocarbon releases (BOP control fluids, well cuttings, produced water) were considered; the remaining potential inputs listed above were not included in the mass balance calculation because it is expected that these substances will be discharged into the Beaufort Sea environment at much lower rates than drilling fluids, sewage, trash and other hydrocarbon sources. Consequently, inputs of metals, nutrient elements and hydrocarbons from these sources are expected to be very small compared to those associated with the discharge of drilling fluids, sewage, trash and the miscellaneous chronic hydrocarbon releases noted above.

4.3.1 Drilling Fluids

The fluxes of various chemical substances resulting from the disposal of drilling fluids are shown in Table 8. Barite ($BaSO_4$), the most abundant component of the typical drilling fluid, is the primary source of metals in the fluids. By comparison, (with the exception of chromium) concentrations of dissolved metals in drilling muds are generally one to four orders of magnitude lower (Bannon et al., 1980). Chromium is the exception because of its presence in the commonly used deflocculent chrome lignosulphonate. (Typical chrome lignosulphonate is 4% chromium by weight and is used in drilling formulations at the rate of 3-43 kg/m^3 (Perricone, 1980).) The calculated fluxes of metals from drilling fluid disposal are based on the use of barite from Mountain Minerals (Alberta) which contains much higher concentrations of metals than many other barites, particularly Battle Mountain Nevada barite which has been used in Beaufort Sea drilling. The metal fluxes shown in Table 8 will tend, therefore, to be a "worst case" estimate. It is assumed that the concentrations of N, P and Si in drilling fluid are not significant for these mass-balance calculations. Note that, as far as the consumption of drilling fluids is concerned, there is no difference between exploration and production well drilling.

4.3.2 Combustion of Fossil Fuels

Another source of anthropogenic metals, hydrocarbons and nutrient elements is the combustion of fossil fuels in ships, production facilities, etc. The projected annual consumption in support of onshore and offshore activities is 2.5×10^5 tonnes in 1990 and 2×10^6 tonnes in the year 2000 (Table 9).

4.3.3 Miscellaneous Hydrocarbons

The prominent inputs of hydrocarbons (through chronic accidental and intentional losses during petroleum exploration and production activities) are BOP control fluids, oil and grease in drill cuttings, oil and grease in produced water and non-catastrophic day-to-day losses from various sources (Table 10). Most of these chronic losses are refined hydrocarbons having low concentrations of metallic and nutrient element impurities (Clark and Brown, 1977). For this reason, no contribution of metals or nutrient elements is included in the mass balance for any of the hydrocarbon sources shown above.

TABLE 8

ANTHROPOGENIC FLUXES DISPOSAL OF DRILLING FLUIDS

A. **Contributions from Barite**

Parameter	Average Composition of Barite* (mmol kg^{-1}) (Note 1)	Quantity Discharged Year 1990 (Note 2)	Quantity Discharged Year 2000 (Note 3)
Cr	0.52	2.5×10^4 mol	4.4×10^4 mol
Ni	0.14	6.9×10^3 mol	1.2×10^4 mol
Cu	0.07	3.3×10^3 mol	5.7×10^3 mol
Zn	29.1	1.3×10^6 mol	2.5×10^6 mol
Cd	0.07	3.3×10^3 mol	5.7×10^3 mol
Hg	0.06	3.0×10^3 mol	5.3×10^3 mol
Pb	3.38	1.6×10^5 mol	2.9×10^5 mol

B. **Contributions from Major Additives to Drilling Fluid**

	Average Composition of Drilling Fluid		
Cr (Note 4)	2.3-33.1 mol m^{-3}	(1.8×10^5 - 2.6×10^6) mol	(3.2×10^5 - 4.7×10^6) mol
Total Hydrocarbons	0.44% Note 5	7.0×10^4 kg	9.2×10^4 kg
N	?	dissolved or soluble forms probably insignificant	
P	?	"	
Si	?	"	

Note 1. Alberta Barite; Thomas, 1978

Note 2. Assumes 39 wells (16 expl. + 23 prod.) each drilled to an average depth of 4000 m and disposal of drilling fluid at the rate of 0.5 m^3 per metre well drilled (4.9×10^7 kg*).

Note 3. Assumes 69 wells (17 expl. + 52 prod.) each drilled to an average depth of 4000 m and disposal of drilling fluid at the rate of 0.5 m^3 per metre well drilled (8.7×10^7 kg*).

Note 4. Typical chrome lignosulphonate contains 4.0% chromium by weight; in general, it is used in drilling formulations at the rate of approximately 3-43 kg/m^3 (Perricone, 1980). In the Beaufort Sea, chrome lignosulphonate content of drilling muds will probably be at the lower end of this range - 2.3 mol/m^3 (see Thomas et al., Table 7-5).

Note 5. Strosher, 1980.

* 1 m^3 drilling fluid contains about 630 kg barite.

TABLE 9. ANTHROPOGENIC FLUXES: COMBUSTION OF FOSSIL FUELS

PARAMETER	AVERAGE CONCENTRATION	REF.	QUANTITY YEAR 1990 (Note 1)	QUANTITY YEAR 2000 (Note 2)
Cr	0.3 mg/L	1	2×10^3 mol	1.6×10^4 mol
Ni	10 mg/L	1	5×10^4 mol	40×10^4 mol
Cu	0.14 mg/L	1	6.8×10^2 mol	54×10^2 mol
Zn	0.25 mg/L	1	12×10^2 mol	96×10^2 mol
Cd	0.01 mg/L	1	3×10^1 mol	2×10^2 mol
Hg	300 µg/L (average)	2	4.6×10^2 mol	4×10^3 mol
Pb	0.3 mg/L	1	5.1×10^2 mol	4×10^3 mol
Total Hydrocarbons	0.8% of fuel supplied to diesel engine is exhausted unburned	3	2×10^6 kg	16×10^6 kg
N	1×10^7 µg/L	2	2×10^8 mol	2×10^9 mol
P	$<10 \times 10^4$ µg/L	2	~1 $\times 10^6$ mol	~ 8 $\times 10^6$ mol
Si	1×10^4 µg/L	2	1×10^5 mol	9×10^5 mol

Ref. 1. Bertine and Goldberg, 1971

Ref. 2. Clark and Brown, 1977

Ref. 3. Hurn, 1968

Note 1. Assumes consumption of 2.5×10^5 tonnes of fuel (specific gravity 0.88) by offshore and onshore operations

Note 2. Assumes consumption of 2×10^6 tonnes of fuel (specific gravity 0.88) by offshore and onshore operations

TABLE 10.

ANTHROPOGENIC FLUXES: MISCELLANEOUS HYDROCARBONS[Note 1]

TYPE OF DISCHARGE	RATE OF DISCHARGE	REF.	ESTIMATED ANNUAL DISCHARGE YEAR, 1990 (16 expl. + 23 prod.) = 39 wells	ESTIMATED ANNUAL DISCHARGE YEAR, 2000 (17 expl. + 52 prod.) = 69 wells
A. CHRONIC RELEASES				
BOP Control Fluid (Note 2)	140 m^3/well/a	1	4.8 x 10^6 kg	8.5 x 10^6 kg
Oil and grease in well cuttings	300 m^3 drill cuttings per well (average oil content is 0.5%) Note 3	2	5.1 x 10^4 kg	9.1 x 10^4 kg
Oil and grease in produced water	produced water approx. equal to concurrent oil production rate; oil and grease content 50 mg/L (max)	3, 4	8.6 x 10^5 kg (Note 4)	3.7 x 10^6 kg (Note 5)
Non-catastrophic accidental hydrocarbon spills, losses	0.01 m^3/well/day; average 0.16 m^3/d all other sources	4	5.7 x 10^6 kg (6.5 x $10^3 m^3$ for 104 wells, cumulative)	3.1 x 10^7 kg (3.6 x $10^4 m^3$ for 573 wells cumulative)
	TOTAL CHRONIC SPILLS		1.1 x 10^7 kg	4.3 x 10^7 kg
B. "CATASTROPHIC" RELEASES (Note 6)				
Oil spills (> 8 m^3)	Rate of spills is worldwide average (~0.1% of offshore production)	5, 6	1.5 x 10^7 kg (1.7 x $10^4 m^3$)	6.5 x 10^7 kg (7.4 x 10^4 kg)

Note 1. Conversion from m^3 to kg "oil" assumes a specific gravity of 0.88.

Note 2. Blowout preventer (BOP) fluid is an antifreeze solution (glycol) used as a hydraulic fluid in BOP stacks during the drilling of a well. It is discharged periodically to the sea floor during testing of the BOP device.

Note 3. 90% of the time well cuttings contain 0% oil; the remaining 10% of the time they may contain up to 5% oil. Thus the average composition is approx. 0.5% (Thomas et al., 1983).

Note 4. produced water discharge rate approx. equal to estimated oil production rate (47 x $10^3 m^3$/d).

Note 5. produced water discharge rate approx. equal to estimated oil production rate (203 x $10^3 m^3$/d).

Note 6. There is no concensus as to how much contiguous oil released into the environment constitutes a "catastrophic" release. If the criterion is the triggering of a response, then the quantity would be very low. If the criterion is significant environmental damage then the quantity would be much higher and vary with circumstance. Here we define a "castastrophic" release as one involving greater than 8 m^3 contiguous oil.

References:

1. ESL, 1982.
2. Thomas et al., 1983.
3. Montreal Engineering, 1981.
4. ESSA, 1980.
5. University of Oklahoma, 1973.
6. Gulf Research and Development Co., 1981.

Fluxes from produced water are calculated on the assumption that at any given time the volume of produced water will be approximately equal to the volume of petroleum produced (Montreal Engineering (Calgary) estimate).

4.3.4 Combustion of Trash

Fluxes arising from the burning of combustible trash (Table 11) are based on an estimated rate of 10 pounds per person per day trash generation and a residue/combusted particulate equivalent of 80 pounds per ton of incinerated trash (Bercha and Associates, 1979). It is further assumed that the residue and fly ash will be totally rendered to the sea and atmosphere. The volatile elements (Cd, Hg, Pb and Zn) will tend to be mobilized to the atmosphere while Cu, Cr and Ni will tend to become enriched in the combustion residue. The hydrocarbon content of the trash will probably be low. After incineration of the hydrocarbons no significant amounts should remain to be mobilized to atmosphere or sea.

4.3.5 Sewage

The fluxes of metals from sewage (Table 12) have been estimated by multiplying the amounts of metals passed by the average person per day (Bryan, 1976) by the number of people expected to be on site in the years 1990 and 2000. This approach was taken because data for the type of future processing, dilution etc., for Beaufort Sea domestic sewage are lacking. The amounts of metals in sewage, nevertheless, would be dominated by human wastes which are relatively constant and well known (see Table 12). No suitable data could be found for nutrients or hydrocarbons.

TABLE 11.

ANTHROPOGENIC FLUXES: COMBUSTION OF TRASH

PARAMETER	AVERAGE COMPOSITION IN COMBUSTED TRASH PARTICULATES[1]	QUANTITY MOBILIZED YEAR 1990[2]	QUANTITY MOBILIZED YEAR 2000[3]
Cr	96 mmol kg^{-1}	3.2×10^4 mol	16×10^4 mol
Ni	0.85 mmol kg^{-1}	2.8×10^2 mol	14.1×10^2 mol
Cu	79 mmol kg^{-1}	2.6×10^4 mol	13.1×10^4 mol
Zn	760 mmol kg^{-1}	2.5×10^5 mol	12.5×10^5 mol
Cd	4.5 mmol kg^{-1}	1.5×10^3 mol	7.4×10^3 mol
Hg	(est.) 5.0 µmol kg^{-1}	1.6 mol	8.2 mol
Pb	240 mmol kg^{-1}	8×10^4 mol	40×10^4 mol
Total Hydrocarbons	?	?	?
N	?	probably insignificant	probably insignificant
P	?	probably insignificant	probably insignificant
Si	?	probably insignificant	probably insignificant

1. Ruppert, 1975.
2. assumes 5000 person labour force and particulates generated at the rate of 66.2 kg/person/year.
3. assumes 25 000 person labour force and particulates generated at the rate of 66.2 kg/person/year.

TABLE 12.

ANTHROPOGENIC FLUXES: SEWAGE

PARAMETER	ANNUAL FLUX PER PERSON[1]	QUANTITY DISCHARGED YEAR 1990[2]	QUANTITY DISCHARGED YEAR 2000[3]
Cr	0.4 mmol	2 mol	10 mol
Ni	?	-	-
Cu	26 mmol	130 mol	650 mol
Zn	70.3 mmol	352 mol	1760 mol
Cd	0.7 mmol	3.5 mol	17.5 mol
Hg	0.01 mmol	0.05 mol	0.25 mol
Pb	0.6 mmol	3 mol	15 mol
Total Hydrocarbons	?	-	-
N	?	-	-
P	?	-	-
Si	?	-	-

1. Bryan, 1976, page 285.
2. based on labour force of 5,000 people.
3. based on labour force of 25,000 people.

5. DISCUSSION

5.1 A Comparison of the Natural and Anthropogenic Fluxes

The anticipated natural flux of metals, hydrocarbons and nutrient elements is compared with the anthropogenic fluxes for the years 1990 and 2000 in Table 13. The ratio of anthropogenic flux to natural flux is a measure of the inputs from industrial activity compared to natural inputs. The ratios are strongly dependent on the chemical parameter. The ratio for hydrocarbons, for instance, is 0.72 and 3.3 for the years 1990 and 2000, respectively, while that for silicate is 3.8×10^{-8} and 3.5×10^{-7} for 1990 and 2000. Put another way, the annual industrial input of hydrocarbons is estimated to be almost equal (0.72) to natural inputs for 1990 but will exceed natural inputs by a factor of 3.28 in the year 2000. On the other extreme, industrial input of silicate is expected to be insignificant (approx. 10^{-8} in 1990; 10^{-7} in 2000) relative to the natural flux. All other chemical parameters fall within the extremes set by the hydrocarbons and silicate. In the year 2000 (considering the Beaufort Shelf as a whole), only the inputs of hydrocarbons will rival natural inputs.

It must be emphasized that the calculations and discussion to this point are based on scenarios and data that are approximate in the context of the constantly evolving plans of the oil companies active in the Beaufort Sea. The recently released Beaufort Sea Environmental Impact Statement suggests that the production rates and anthropogenic fluxes will probably be somewhat less than those upon which this mass-balance has been constructed (Dome Petroleum Limited, Volume 1, 1982). Consequently, this mass balance is a "worst case" treatment according to the most up-to-date information available. In addition, the calculations are also based on considering the entire 60,000 km^2 study area as a whole. It is possible that specific local effects or development activities might result in completely different results, but such occurrences should be infrequent. The Tarsiut Development was chosen to allow examination of the relationship between natural and anthropogenic fluxes within a more limited geographical context. The data in Table 14 are arranged so that the rate of anthropogenic input can be compared to the natural fluxes during periods of maximum and minimum river transport. The estimates for anthropogenic flux are based on projections for 1990 adjusted for the proportion of total 1990 activity anticipated at Tarsiut. During peak river flow (June to September), only thedrilling related inputs of hydrocarbons exceed natural inputs; Hg and Pb are approximately equal for both inputs;

TABLE 13.

COMPARISON OF NATURAL AND ANTHROPOGENIC FLUXES
FOR PRODUCTION SCENARIOS IN THE YEARS 1990 and 2000

PARAMETER	NATURAL FLUX A	ANTHROPOGENIC FLUX 1990 B	B/A*	ANTHROPOGENIC FLUX 2000 C	C/A*
Cr (mol)	(6.4 - 6.8) x 10^7	2.2 x 10^5	0.0016	5.1 x 10^5	0.0080
Ni (mol)	(23 - 38) x 10^7	8.6 x 10^4	0.0004	5.4 x 10^5	0.0023
Cu (mol)	(11.5 - 18) x 10^7	5.7 x 10^4	0.0005	2.6 x 10^5	0.0023
Zn (mol)	(42 - 46) x 10^7	1.6 x 10^6	0.0038	3.9 x 10^6	0.0093
Cd (mol)	(5.2 - 13.6) x 10^6	6.6 x 10^3	0.0013	2.0 x 10^4	0.0038
Hg (mol)	(15.1 - 20.6) x 10^4	3.5 x 10^3	0.0230	9.4 x 10^3	0.0620
Pb (mol)	(6.4 - 29.2) x 10^6	2.4 x 10^5	0.0380	4.0 x 10^5	0.0630
Total Hydrocarbons (kg)	(est) 1.8 x 10^7	1.3 x 10^7	0.72	5.9 x 10^7	3.3
N (mol)	4.8 x 10^{10}	2 x 10^8	0.004	2 x 10^9	0.042
P (mol)	6.0 x 10^9	1 x 10^6	0.0002	8 x 10^6	0.001
Si (mol)	2.6 x 10^{12}	1 x 10^5	3.8 x 10^{-8}	9 x 10^5	3.5 x 10^{-7}

* Value for A is taken as lower end of range ("worst case" calculation).

TABLE 14.

NATURAL vs ANTHROPOGENIC FLUXES:
A SITE-SPECIFIC EXAMPLE - THE TARSIUT DEVELOPMENT[1,2]

PARAMETER	NATURAL FLUX ANNUAL	NATURAL FLUX AVERAGE DAILY SUMMER RATE[3]	NATURAL FLUX AVERAGE DAILY WINTER RATE[4]	ESTIMATED ANTHROPOGENIC FLUX 1990 ANNUAL	ESTIMATED ANTHROPOGENIC FLUX 1990 AVERAGE DAILY[5]
Cr (mol)	(11.1 - 11.8) x 10^4	865 - 919	23 - 2.5	8.2 x 10^4	225
Ni (mol)	(39.8 - 65.7) x 10^4	3100 - 5120	19 - 138	3.2 x 10^4	88
Cu (mol)	(19.9 - 31.1) x 10^4	1550 - 2420	42 - 65	2.1 x 10^4	58
Zn (mol)	(72.7 - 79.6) x 10^4	5660 - 6200	133 - 167	6.0 x 10^5	1.6 x 10^3
Cd (mol)	(9.0 - 23.5) x 10^3	700 - 1830	19 - 49	2.5 x 10^3	6.8
Hg (mol)	(2.6 - 3.6) x 10^2	2.0 - 2.8	0.055 - 0.076	1.3 x 10^3	3.6
Pb (mol)	(11.1 - 50.5) x 10^3	86 - 393	2.3 - 10.6	8.9 x 10^4	244
Total Hydrocarbons (kg)	(est) 3.1 x 10^4	241	6.5	4.8 x 10^6	1.3 x 10^4

1. General data: size of oil field = 104 km^2
   maximum anticipated rate of oil production = 17 500 m^3/d (=37.2% of total 1990 production)
   proportion of total natural flux affecting oil field area = 0.173%
2. This is a "worst case" scenario using contaminated barite.
3. Average daily transport June - August is 0.779% of annual total.
4. Average daily transport September - May is 0.021% of annual total.
5. Assumes even annual distribution of discharge.

and natural fluxes of Cr, Ni, Cu, Zn and Cd easily exceed anthropogenic fluxes. At the other extreme of the natural cycle, during the winter period (averaged over the months October to May), anthropogenic inputs for Hg, Cr, Pb, Zn and hydrocarbons exceed natural ones; Ni and Cu are approximately equal and the natural input of Cd exceeds the anthropogenic input. These estimates provide a "worst case" scenario because they assume that all discharges associated with the Tarsiut area will impact directly on the oil field area.

According to the anticipated scheduling of the Tarsiut development, the maximum number of new wells per year at peak activity would be 24. If all the discharged barite were to deposit evenly within a 500-m radius at each of these wells with a porosity of 50%, then a layer 0.07 cm thick would form. This is about one-third the estimated natural sedimentation rate of 0.22 cm/y for the same area (see Table 3).

5.2 Dredging

The Beaufort Sea Development Plan requires that a large amount of sediment must be relocated by dredges during the construction of artificial drilling islands, APLAs etc. During peak activity in 1990 it is projected that dredging will move approximately 111×10^6 m^3 of sediment. This exceeds the total annual particulate transport of the Mackenzie River by about 25%. In other years, the river will be expected to dominate. By comparison, an annual total of 27.6×10^6 m^3 of material comprising dredge spoils, sewage sludge, acid waste, chemical waste and building and construction debris is discharged into the shallow waters of the New York Bight Apex which has an area of approximately 718 km^2 (Gunnerson, 1981). This exceeds natural sediment flux by a factor of 2 on a continuing basis.

REFERENCES

Bannon, P., J. McComiskey and R. Sempkin, 1980. Environmental review of the 1979 Beaufort Sea offshore drilling program and overview of 1976-79. Indian and Northern Affairs, Northern Affairs Program, 55 pp.

Bercha F.G. and Associates Limited, 1979. Zone of influence of other offshore activities. Volume 1. A report prepared for Dome Petroleum Limited. Unpublished manuscript.

Bertine, K.K., and E.D. Goldberg, 1971. Fossil fuel combustion and the major sedimentary cycle. Science 173, 233-235.

Brunskill, G.J., P. Campbell, S.E.M. Elliott, B.W. Graham, W.J. Dentry and R. Wagemann 1975. The chemistry, mineralogy and rates of transport of sediments in the Mackenzie and Porcupine River water sheds, N.W.T. and Yukon, 1971-73. Environment Canada Technical Report No. 546, 69 pp.

Bryan, G.W., 1976. Heavy metal contamination in the Sea. (In) Marine Pollution, Academic Press, London pp. 185-302.

Cawse, P.A., 1980. Deposition of trace elements from the atmosphere in the UK. U.K. At. Energy Res. Establ. Rep., AERE-R-9484. 22 pp.

Clark, R.C. Jr., and D.W. Brown, 1977. Petroleum: Properties and Analyses in Biotic and Abiotic Systems. (In) Effects of Petroleum on Arctic and Subarctic Marine Environments and Organisms D.C. Malins (Ed). Academic Press, New York, pp. 1-89.

Davies, K.F., 1975 Mackenzie River input to the Beaufort Sea. Beaufort Sea Technical Report No. 15. Beaufort Sea Project, Victoria, B.C., 11 pp. + Tables.

Dome Petroleum Limited, 1982. Environmental Impact Statement Volume 1. Summary. Chapter 1. Energy need, development plan, and Canadian benefits.

Environment Canada, 1981. Mackenzie River Basin Water Quality Data. 1960-1974 Environment Canada, Ottawa.

ESL Environmental Sciences Limited, 1982. The biological effects of hydrocarbon exploration and production related activities on marine flora and fauna of the Beaufort Sea region. Prep. for Dome Petroleum Ltd., Calgary, Alberta. Supporting Doc. to the Dome Esso and Gulf Hydrocarbon Development in the Beaufort Sea - Mackenzie Delta Region Environmental Impact Statement.

ESSA, 1980. Beaufort Sea Production Scenario Model. A report prepared by ESSA Environmental and Social Systems Analysts Ltd for Dome Petroleum Limited, 69 pp.

Goodwin, R.J., W.P. Warlick, P. Teymourian and W.F. Krieger, 1981. Analysis of accidents in offshore operations where hydrocarbons were lost. A report prepared by Houston Technical Services Centre and Gulf Research and Development Company for Gulf Canada Resources Inc. 111 pp.

Gunnerson, C.G., 1981. The New York Bight ecosystem. (In) Marine Environmental Pollution pp. 313-78. Elsevier Oceanographic Series, Volume 27B. Amsterdam.

Harper, J.R. and S. Penland, 1982. Beaufort Sea Sediment Dynamics. A report prepared for the Geological Survey of Canada by Woodward-Clyde Consultants. Unpublished manuscript, 198 pp.

Herlinveaux, R.H., B.R. de Lange Boom and G.R. Wilton, 1976. Salinity, Temperature, Turbidity and Meteorological Observations in the Beaufort Sea: Summer 1974, Spring and Summer, 1975. Pacific Marine Science Report 76-26. Institute of Ocean Sciences, Patricia Bay, 244 pp.

Hurn, R.W., 1968. Mobile Combustion Sources. (In) Air Pollution Volume III. A.C. Stern (Ed) Academic Press, New York, pp. 55-93.

Li, Y-H., 1981. Geochemical cycles of elements and human perturbation. Geochim. Cosmochim. Acta 45, 2073-2084.

Milliman, J.D. and R.H. Meade, 1983. World-wide delivery of river sediment to the oceans. J. Geol. 91(1), 1-23.

Montreal Engineering Company Limited, 1981. EIA - Beaufort Sea Development. Volume IV, Environmental effects of normal operations. Draft report prepared by Montreal Engineering, Calgary, Alberta for Dome Petroleum Limited. Unpublished manuscript.

Nriagu, J.O., 1979. Copper in the atmosphere and precipitation (In) Copper in the Environment. Part I. Ecological Cycling. J.O. Nriagu (Ed). Wiley Interscience, New York, pp. 43-76.

Nriagu, J.O., 1980. Zinc in the atmosphere. (In) Zinc in the Environment. Part I Ecological cycling. J.O. Nriagu (Ed). Wiley Interscience, New York, pp. 113-160.

Nriagu, J.O., 1980. Cadmium in the atmosphere and in precipitation. (In) Cadmium in the Environment Part I. Ecological cycling J.O. Nriagu (Ed). Wiley Interscience, New York, pp. 71-114.

Peake, E., B.L. Baker and G.W. Hodgson, 1972. Hydrogeochemistry of the surface waters of the Mackenzie River drainage basin, Canada-II. The contribution of amino acids, hydrocarbons and chlorins to the Beaufort Sea by the Mackenzie River system. Geochim. Cosmochim. Acta 36, 867-883.

Perricone, C., 1980. Major drilling fluid additives - 1979. (In) Research on Environmental Fate and Effects of Drilling Fluids and Cuttings. A symposium held at Lake Buena Vista, Florida, January 21-24 1980. pp. 15-29.

Reeder, S.W., B. Hitchon, and A.A. Levinson 1972. Hydrogeochemistry of the surface waters of the Mackenzie River drainage basin, Canada-I. Factors controlling inorganic composition Geochim. Cosmochim. Acta 36, 825-865.

Ruppert, H., 1975. Geochemical investigations on atmospheric precipitation in a medium-sized city (Gottingen, FRG). Water, Air and Soil Pollution 4, 447-460.

Schmidt, J.A., and A.W. Andren, 1980. The atmosphere chemistry of nickel. (In) Nickel in the Environment. J.O. Nriagu (Ed). Wiley Interscience, New York, pp. 93-136.

Shaw, D.G. and B.A. Baker, 1978. Hydrocarbons in the marine environment of Port Valdez, Alaska. Env. Sci. and Tech. 12 (10), 1200-1205.

Strosher, N.T., 1980. Characterization of organic constituents in waste drilling fluids. (In) Research on Environmental Fate and Effects of Drilling Fluids and Cuttings. A symposium held at Lake Buena Vista Florida, January 21-24, 1980, pp. 70-97.

Subramanian, V., and K.K. Saxena, 1980. Chemistry of monsoon rainwater and Delhi. Tellus 32, 558-561.

Tanner T.M., L.a. Rancitelli and W.A. Haller, 1972. Multi element analysis of natural waters by neutron activation, group chemical separations and gamma ray spectrometric techniques. Water, Air and Soil Pollution 1, 132-143.

Thomas, D.J., 1978. Total and Extractable iron, chromium, cadmium, nickel, lead, zinc, copper, and mercury in 83 Alberta barite samples. An unpublished data report prepared for Dome Petroleum Limited by Seakem Oceanography, Sidney, B.C., 12 pp.

Thomas, D.J., R.W. Macdonald and A.B. Cornford, 1983. Arctic Data Compilation and Appraisal Volume 2. Beaufort Sea: Chemical Oceanography. Can. Data Report of Hydrography and Ocean Sciences 5(2), 238 pp.

Thomas, D.J., G.D. Greene, W.S. Duval and K.C. Milne, 1983. Offshore oil and gas production waste characteristics, treatment methods, biological effects and their application to Canadian regions. A draft report prepared jointly by Arctic Laboratories Limited, ESL Environmental Sciences Limited and SKM Consulting Limited for the Environmental Protection Service, Water Pollution Control Directorate, Ottawa, Ontario. 363 pp.

University of Oklahoma, 1973. Energy Under the Oceans. University of Oklahoma Press, Norman, Oklahoma.

Wagemann R., G.J. Brunskill and B.W. Graham, 1977. Composition and reactivity of some river sediments from the Mackenzie Valley, N.W.T., Canada. Env. Geol. 1, 349-358.

Water Survey of Canada, 1980. Unpublished data sheets. Calgary Alberta Jan 01, 1980.

Whitfield, P.H and H. Schreier, 1981. Hysteresis in relationships between discharge and water chemistry in the Fraser River basin, British Columbia. Limnol. Oceanogr., 26(6), pp. 1179-1182.

Wong, C.S., W.J. Cretney, P. Christensen and R.W. Macdonald, 1976. Hydrocarbon levels in the marine environment of the southern Beaufort Sea. Beaufort Sea Technical Report No. 38. Beaufort Sea Project, Victoria, B.C., 113 pp.

Yadav, A.K. and G.P. Mishra, 1979. Chemistry of rainwater and its contribution to nutrient input in forests of central India. Tellus 31, 463-464.

OTHER RELATED PUBLICATIONS

1. Cornford, A.B., D.D. Lemon, D.B. Fissel, H. Melling, B.D. Smiley, R.H. Herlinveaux and R.W. Macdonald. Arctic Data Compilation and Appraisal. Volume 1. Beaufort Sea: Physical Oceanography - Temperature, Salinity, Currents and Water Levels. Can. Data Rep. Hydrogr. Ocean Sci. 5: (Volume 1) 279 pp.

2. Thomas, D.J., R.W. Macdonald and A.B. Cornford. Arctic Data Compilation and Appraisal. Volume 2. Beaufort Sea: Chemical Oceanography. Can. Data Rep. Hydrogr. Ocean Sci. 5: (Volume 2) 243 pp.

3. Birch, J.R., D.B. Fissel, D.D. Lemon, A.B. Cornford, R.A. Lake, B.D. Smiley, R.W. Macdonald and R.H. Herlinveaux. Arctic Data Compilation and Appraisal. Volume 3. Northwest Passage: Physical Oceanography -Temperature, Salinity, Currents and Water Levels. Can. Data Rep. Hydrogr. Ocean Sci. 5: (Volume 3) 262 pp.

4. Thomas, D.J., R.W. Macdonald and A.B. Cornford. Arctic Data Compilation and Appraisal. Volume 4. Northwest Passage: Chemical Oceanography. Can. Data Rep. Hydrogr. Ocean Sci. 5: (Volume 4) 200 pp.

5. Birch, J.R., D.B. Fissel, D.D. Lemon, A.B. Cornford, R.H. Herlinveaux, R.A. Lake and B.D. Smiley. Arctic Data Compilation and Appraisal. Volume 5. Baffin Bay: Physical Oceanography - Temperature, Salinity, Current and Water Levels. Can. Data Rep. Hydrogr. Ocean Sci. (Volume 5) 372 pp.

6. Fissel, D.B., L. Cuypers, D.D. Lemon, J.R. Birch, A.B. Cornford, R.A. Lake, B.D. Smiley, R.W. Macdonald and R.H. Herlinveaux. Arctic Data Compilation and Appraisal. Volume 6. Queen Elizabeth Islands: Physical Oceanography - Temperature, Salinity, Currents and Water Levels. Can. Data Rep. Hydrogr. Ocean Sci. (Volume 6) in press.

POOR

QUALITY

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